Beyond the Standard Model

on the lattice

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Current and past research USQCD/LQCD:

- Searching for viable technicolor theories for electroweak symmetry breaking
- Lattice supersymmetry
  - Formulations with exact SUSY
  - Use of DWF to study N=1 SYM

Technicolor – basic idea

- Dispense with elementary Higgs in SM
- Assume new (techni)-fermions carrying EW quantum numbers
- New strong force causes condensation

$$\langle \overline{Q}Q \rangle = \Lambda_{TC}^3 = O(250GeV)^3$$

Goldstones from breaking chiral symmetries eaten to produce massive M_W,Z

Advantages

- No fine tuning Higgs mass $m_H \sim O(\Lambda)$
- No triviality problem $\lambda \to 0$ $\Lambda \to \infty$
- EW scale naturally small if asymptotically free

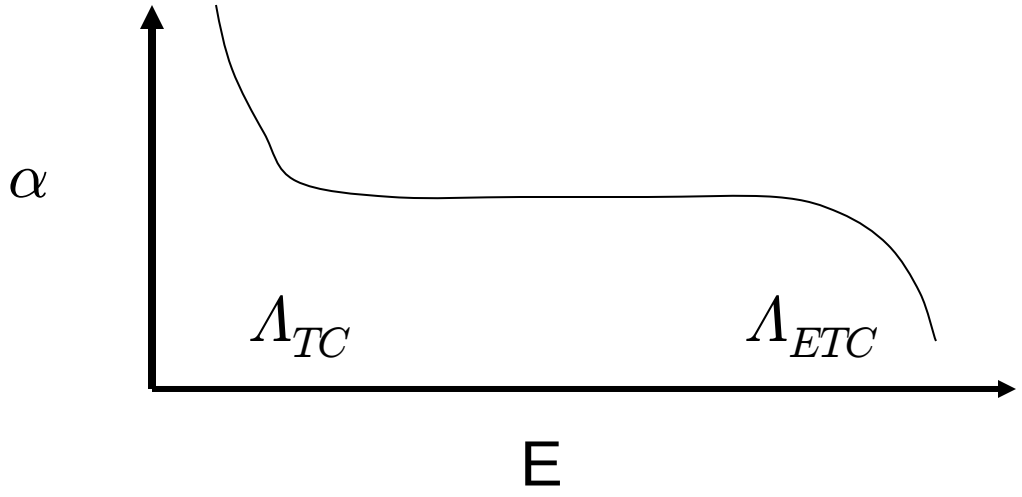
BUT

What gauge group, number flavors, representation ?

Problems …

- Scaled up QCD ($\Lambda_{QCD} \rightarrow \Lambda_{TC}$) impossible
  - precision electroweak measurements at LEP would have seen it
  - To give masses to SM fermions need to couple to techniquarks in ETC theory at scale Λ_{ETC}
  - Energies E<Λ_{ETC} → 4-fermion ops → SM mass terms after techniquarks condense.
  - Absence of FCNC → large Λ_{ETC} but then SM fermion masses too small ..

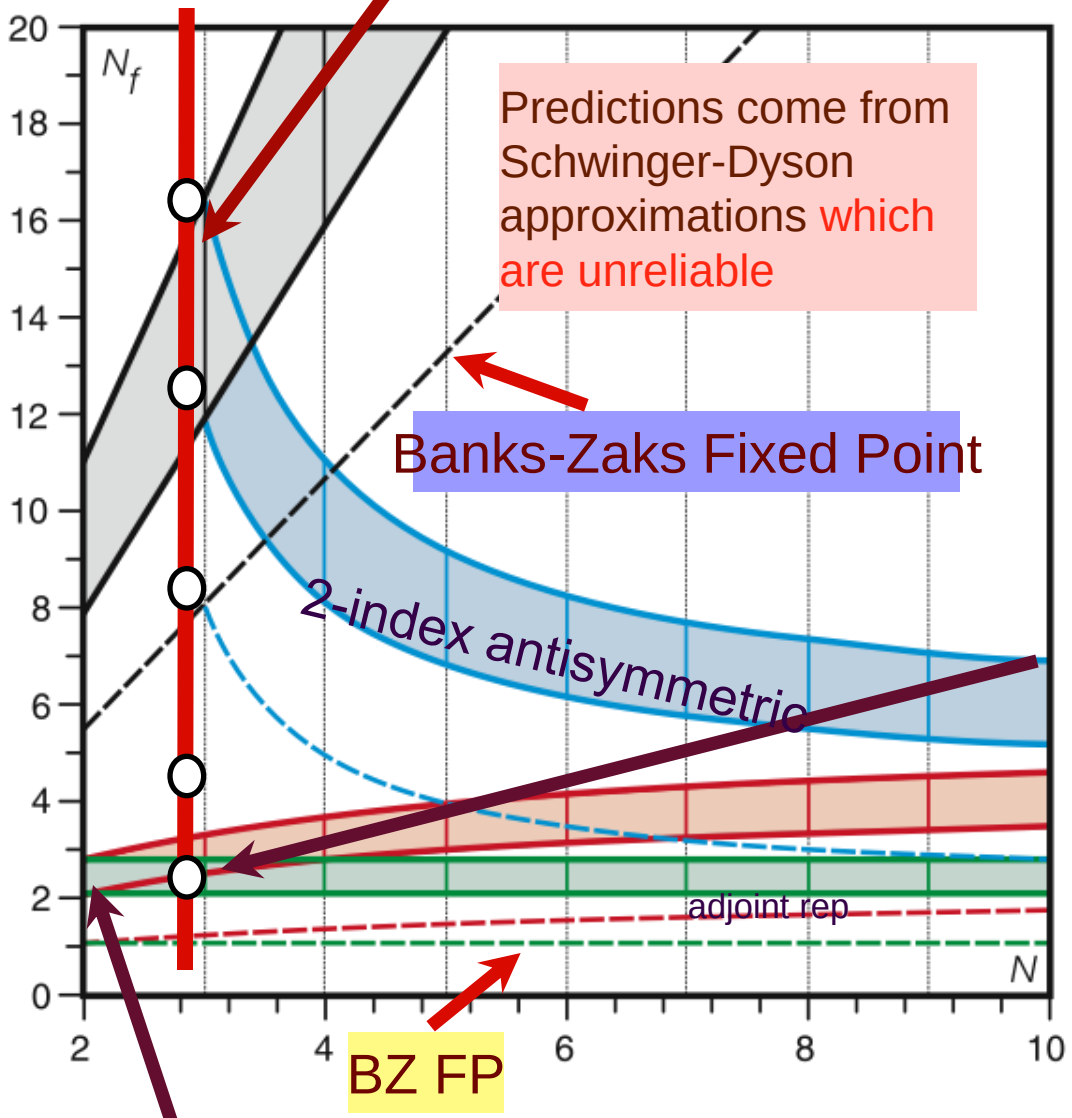
Solution – walking dynamics



Need to search theory space for conformal theories

Enhances SM fermion masses.
Reduces contributions to S parameter
Strongly coupled but eg spectrum very different to QCD

Theory space studied by LSD, LHC



Conformal in window
$N_f^1 < N_f < N_f^2$

LHC sextet model

Sannino et al 2007

MWT model $N_f=N_c=2$

3 groups within USQCD

- Syracuse/RPI/U. S. Denmark
- Lattice Strong Dynamics LSD
- Lattice Higgs Collaboration LHC

Syracuse/RPI/Denmark

Simon Catterall, Joel Giedt, Francesco Sannino, ..

- Minimal Walking Technicolor model

  N_f=2 adj SU(2)

  smallest N_f for (near) conformality ?

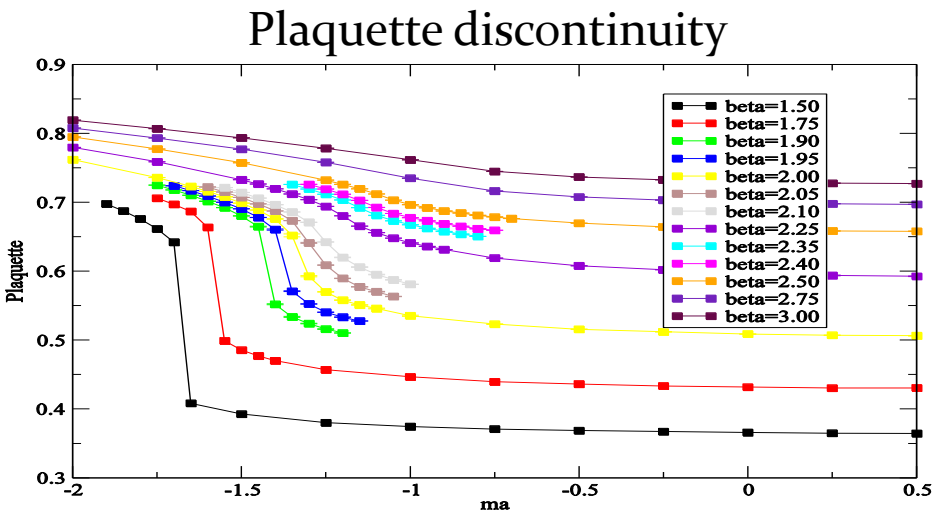
- Good place to test tools/techniques for studying such theories where naively need lattices L>1/Λ

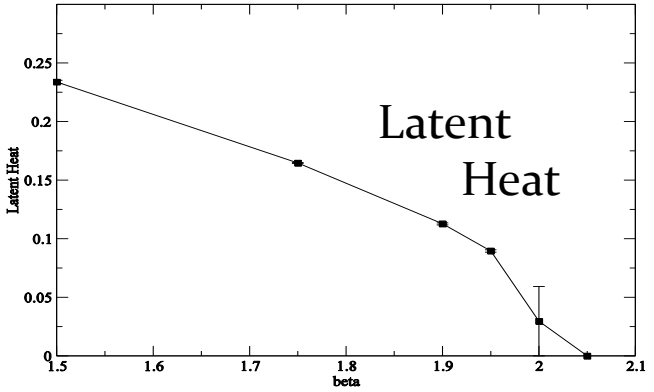
$$\Lambda = e^{-\int \frac{dg}{\beta(g)}}$$ ⟵ (very) small

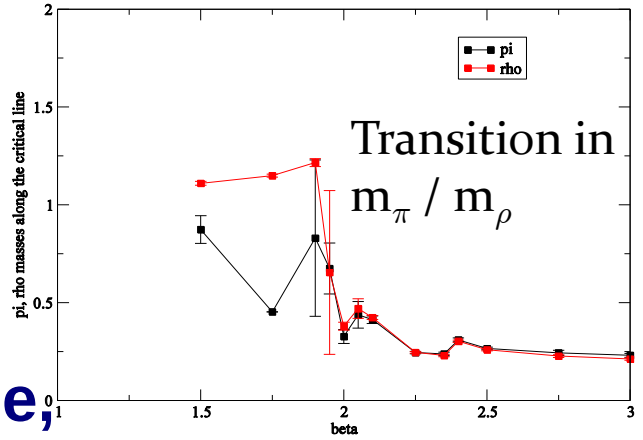
Minimal Walking TC

1.0 M hrs+ 0.7 M hrs BG/L

O(100) parameter pts
8^3x16 Wilson







Catterall, Sannino,
Phys.Rev.D76:034504,2007
Catterall, Giedt, Sannino, Schneible,
JHEP 0811:009,2008.

Syracuse/RPI current projects

- Current 16^3x32 clover, ϵ -regime
  - Condensate $<\psi\psi>$ function of m_{PCAC}
- Exploit conformal map: $R^4 \rightarrow S^3 \times R$ and use finite size scaling

$$m_{\text{semi-finite geometry}} = \frac{2\pi\Delta}{L}$$

Lattice Strong Dynamics (LSD) Collaboration

http://www.yale.edu/LSD

James Osborn

Ron Babich
Rich Brower
Mike Clark
Claudio Rebbi
David Schaich

Saul Cohen

Michael Cheng
Ron Soltz
Pavlos Vranas

Joe Kiskis

Tom Appelquist
George Fleming
Ethan Neil

LSD Research Program

- Starting from QCD, study how the low energy structure varies as N_f increases towards the conformal window.
- Low energy structure includes:
  - Low energy constants of chiral perturbation theory: B, F
  - Light hadron spectrum
  - Static potential
  - Peskin-Takeuchi S parameter (L_{10} in NLO ChiPT)

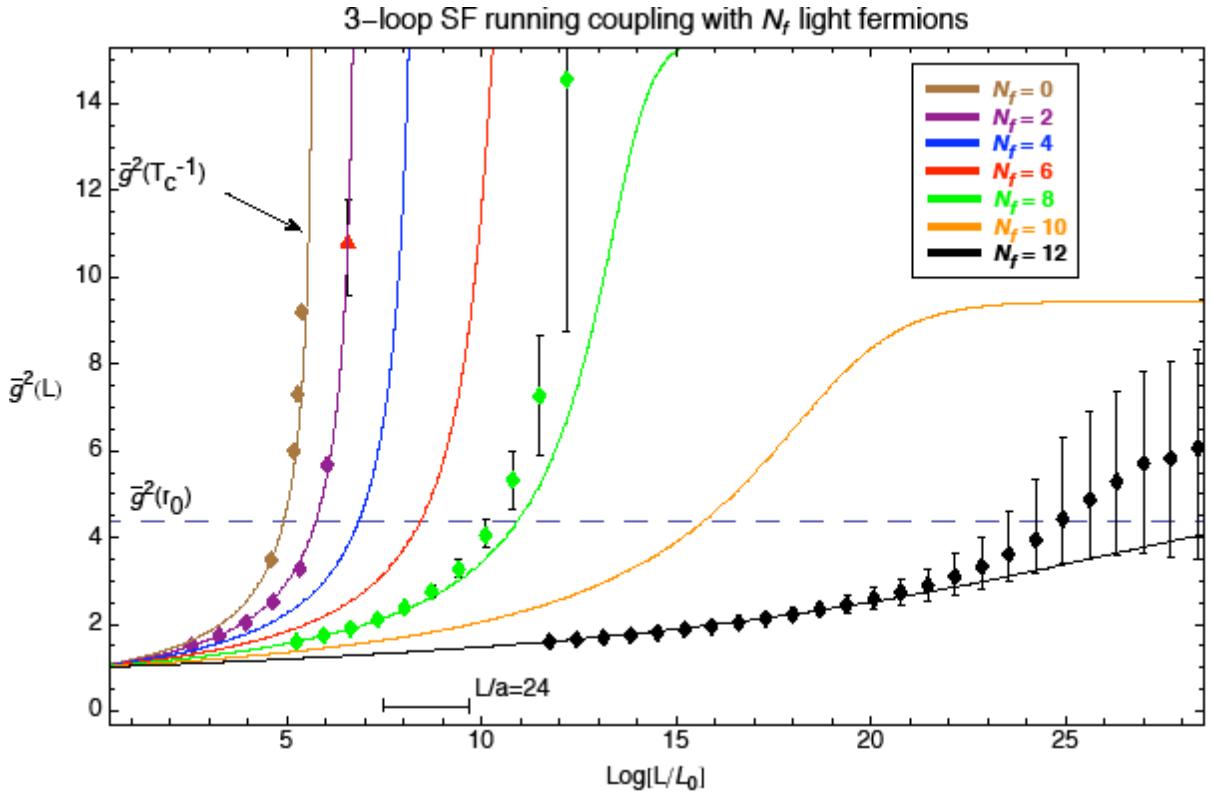
LSD configs done

- SU(3), N_f=6, 24^3x32 DWF

quark mass	no. configs
0.04	480
0.0266	390
0.02	350
0.0133	355

Currently – dedicated time on 4000 nodes QCDOC
20 M node hrs

Appelquist, Fleming, Neil, Phys. Rev. D79, 076010 (2009)
Phys.Rev.Lett.100:171607,2008



Running coupling in SU(3) varying N_f

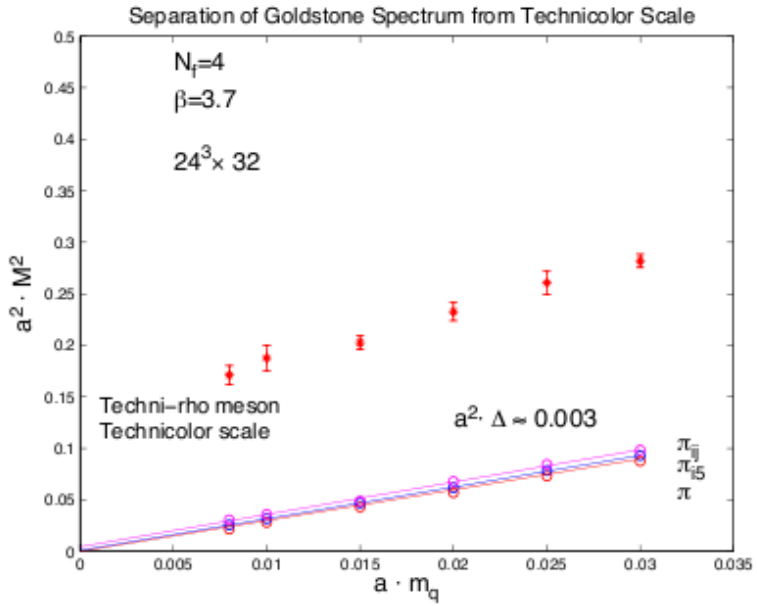
N_f=10 SU(3) fund. In conformal window ?

LHC collaboration

Kuti, Fodor, Holland, Nogradi, Schroeder
UCSD, U Pacific

Current projects:

- SU(3) with N_f=2 sextet quarks (dynamical overlap)
- SU(3) with N_f=4-16 fund quarks (staggered)
  - ϵ -regime and chiral regime
- Running gauge coupling from Wilson loops
- Lattices 16^4-28^4, 3.6 M hrs CPU LQCD



At beta=3.7 Goldstone spectrum collapses

Dirac eigenvalues form almost degenerate quartets (this is what we want)

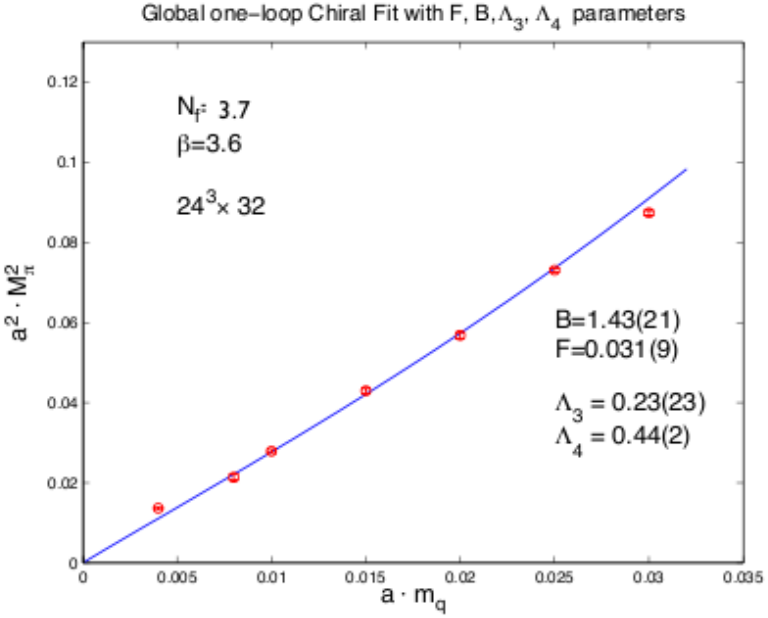
p-regime chiral loop analysis and RMT work simultaneously

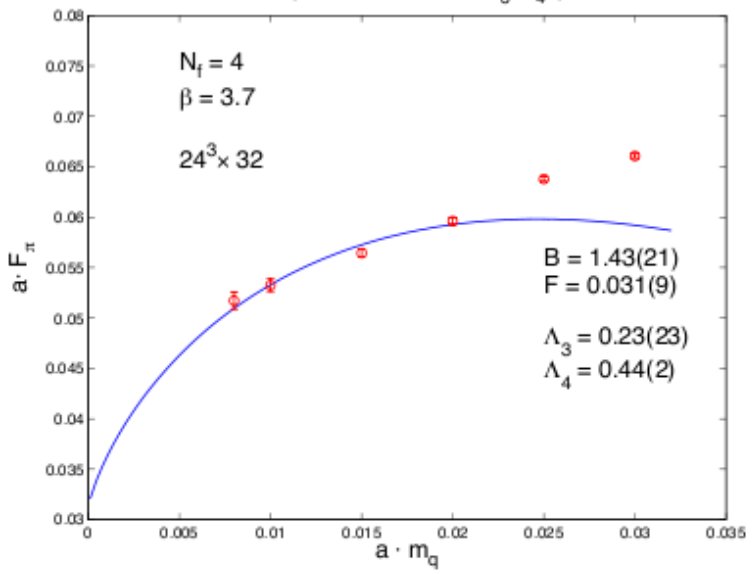
stringent test of chiral phase

Nf=8,12 ? We are doing it now

p-regime test is increasingly difficult as we approach the conformal window

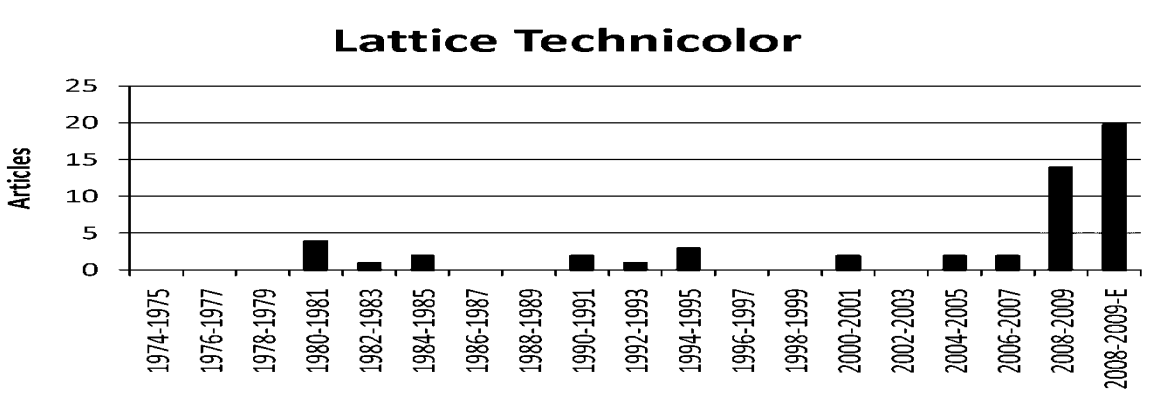
Nf=4 staggered fermion (restored taste symmetry) and continuum limit reached





Lattice Technicolor picking up steam

3 out of 7 groups currently active internationally in lattice technicolor are part of USQCD



2009 extrapolated last bar (E)

Supersymmetry SUSY

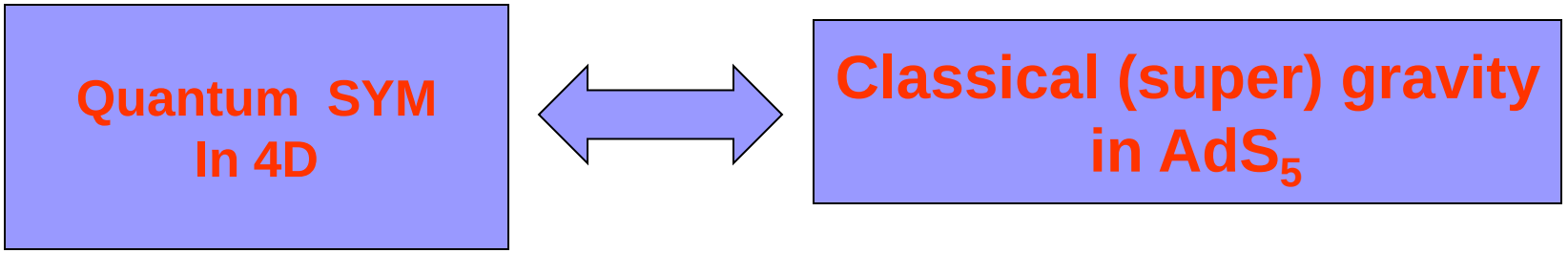
Motivations: another (popular!) extension of Standard Model:

- Higgs mass light
- Improves unification of couplings at MGUT=O(10^{15}) GeV
- Necessary ingredient String Theory
  - AdSCFT – quantum gravity and gauge theory

Lattice supersymmetry

- Old hard problem. New developments:
  - Certain models can be discretized preserving some SUSY exactly
- Most interesting: $\mathcal{N}$=4 SYM

AdSCFT correspondence:



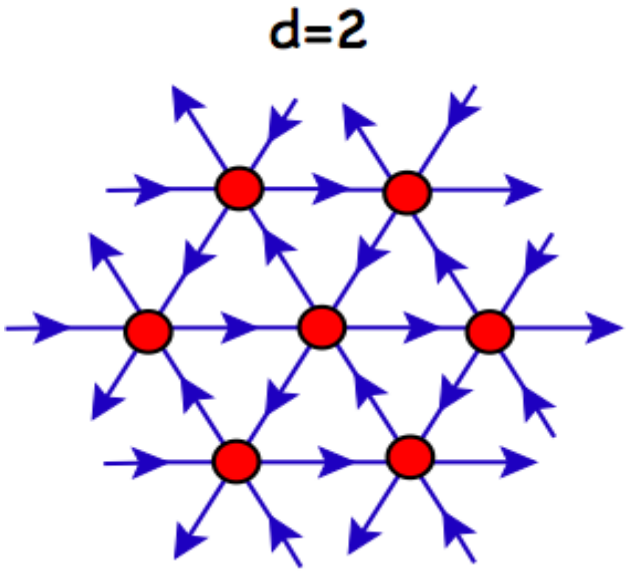
$\mathcal{N}$=4 lattice theory

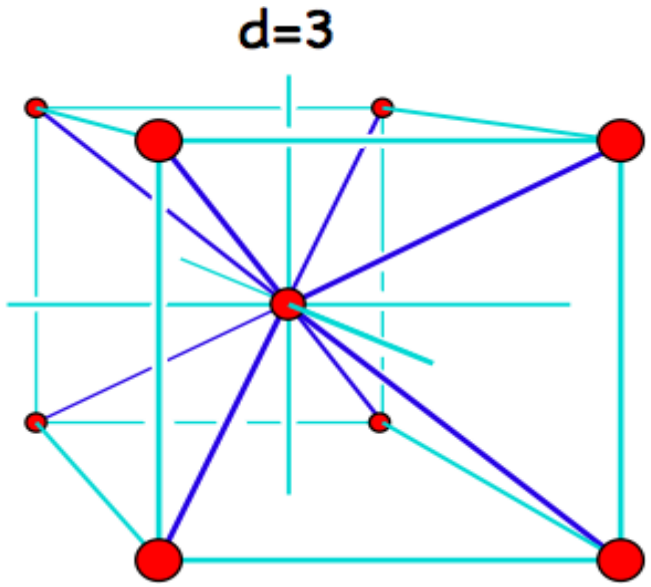
New ideas orbifolding/topological twisting

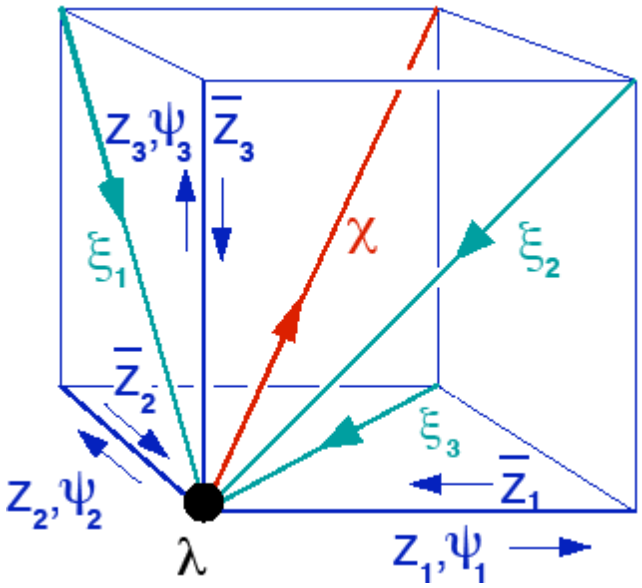
USQCD international leadership position

Kaplan, Catterall, Unsal **arXiv:0903.4881**, upcoming Phys. Rep.

Theory is local, gauge invariant, supersymmetric, free of doublers

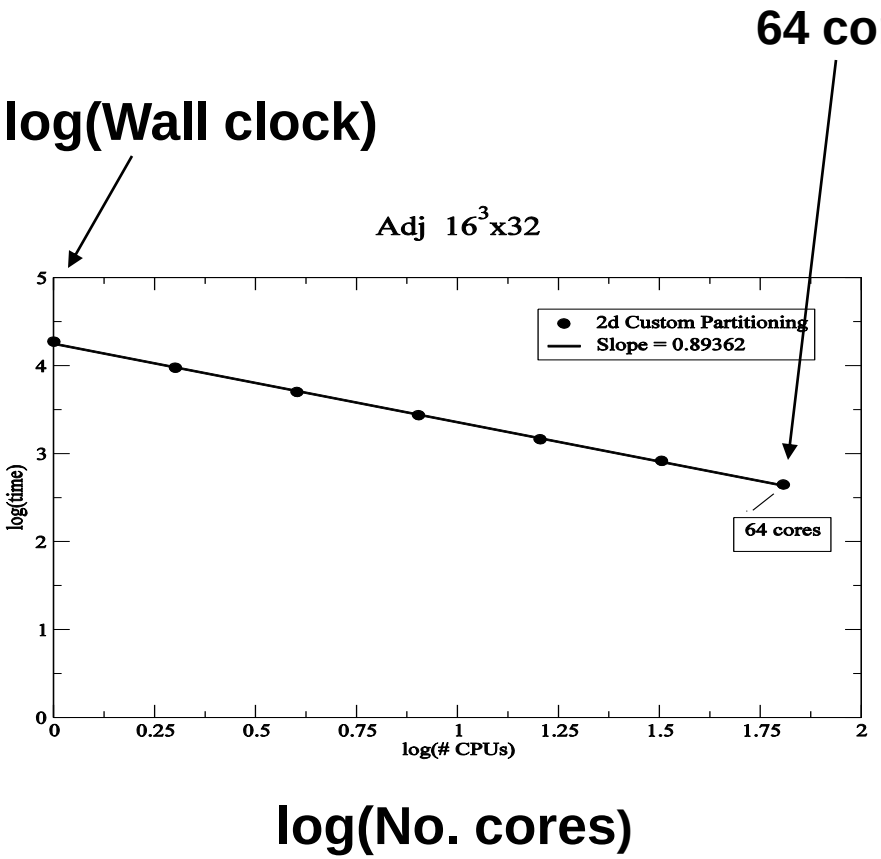






Fermions and bosons live on links.
Gauge links include
Scalars – complex
Fermions equivalent to staggered

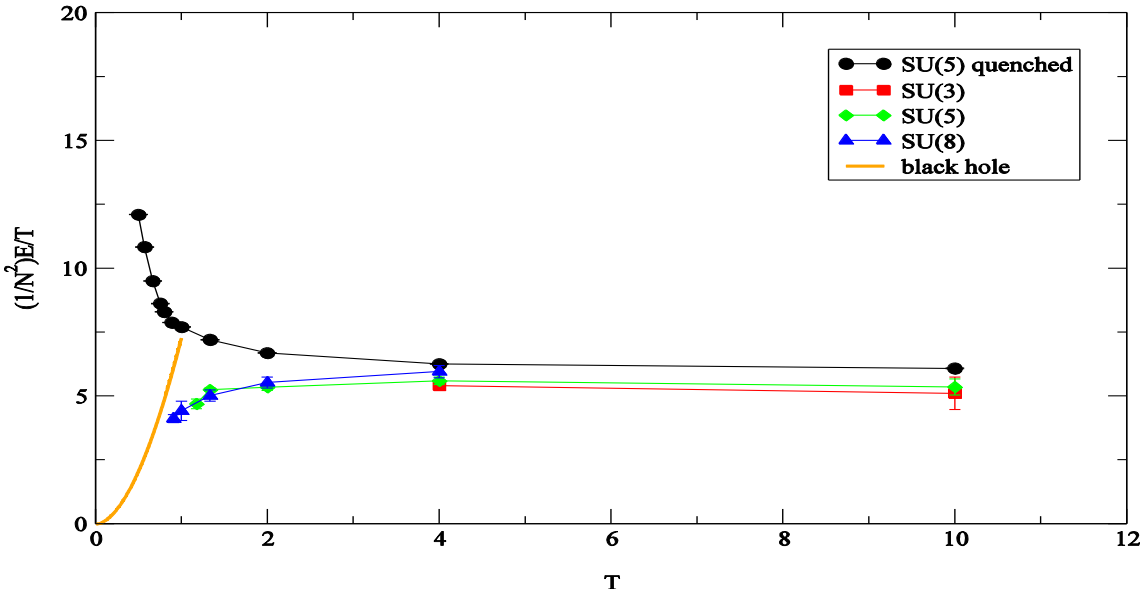
Codes



- C++ codes written from scratch
- Use MDP libraries in FermiQCD
- Standard lattice QCD algs. eg RHMC
- Catterall **JHEP0901:040,2009**

Example of AdSCFT

- SYM quantum mechanics describes black holes in AdS_5



Catterall, Wiseman
Phys.Rev.D78:041502,2008
JHEP 0712:104,2007

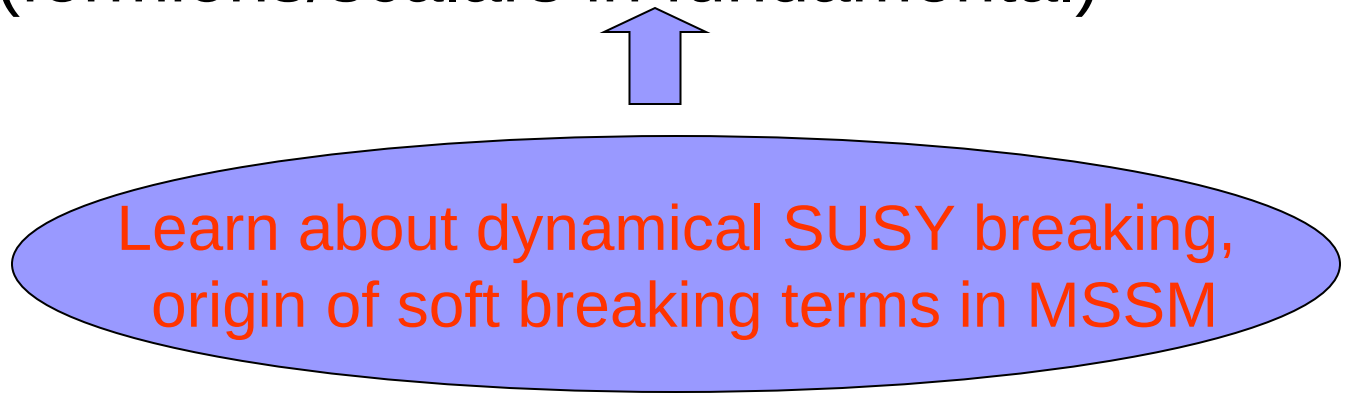
0.25 M hrs LQCD

$\mathcal{N}$=4 program

- Explore/test AdSCFT conjecture
  - Non BPS quantities – eg geometry impossible analytically
- Dual gauge theories always strongly coupled – great opportunity for lattice
  - D=2 SYM, BMN model
- Break $\mathcal{N}$=4 → better route to $\mathcal{N}$=1 ?

$\mathcal{N}$=1 super Yang-Mills

- Why ?
  - Core component Minimal Supersymmetric Standard Model MSSM
  - Stepping stone to **super QCD** (fermions/scalars in fundamental)



DWF for $\mathcal{N}$=1 SYM

- Cannot use tricks to make lattice theory exactly SUSY invariant.
- However only relevant SUSY violating operator is gaugino mass
- Absent for domain wall fermions DWF

Expect SUSY restored without fine tuning in continuum limit

USQCD groups:

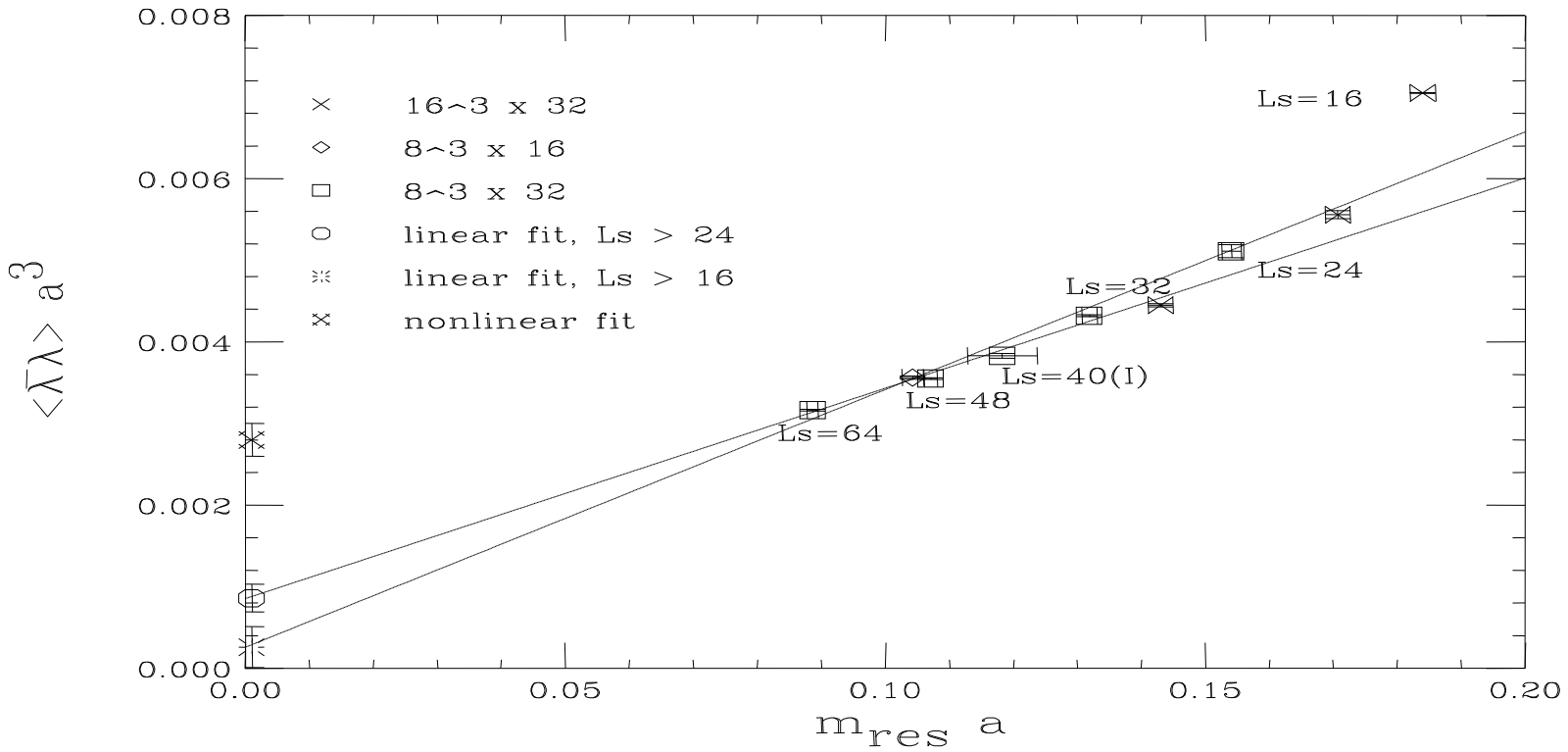
- Endres (**arXiv:0902.4267**, **arXiv:0810.0431**)
- Giedt, Brower, Catterall, Fleming,Vranas

  (**Phys.Rev.D79:025015,2009**,**arXiv:0807.2032**)

Gaugino condensate

$$\langle \lambda\lambda \rangle \neq 0$$

Chiral extrapolation at β=2.3

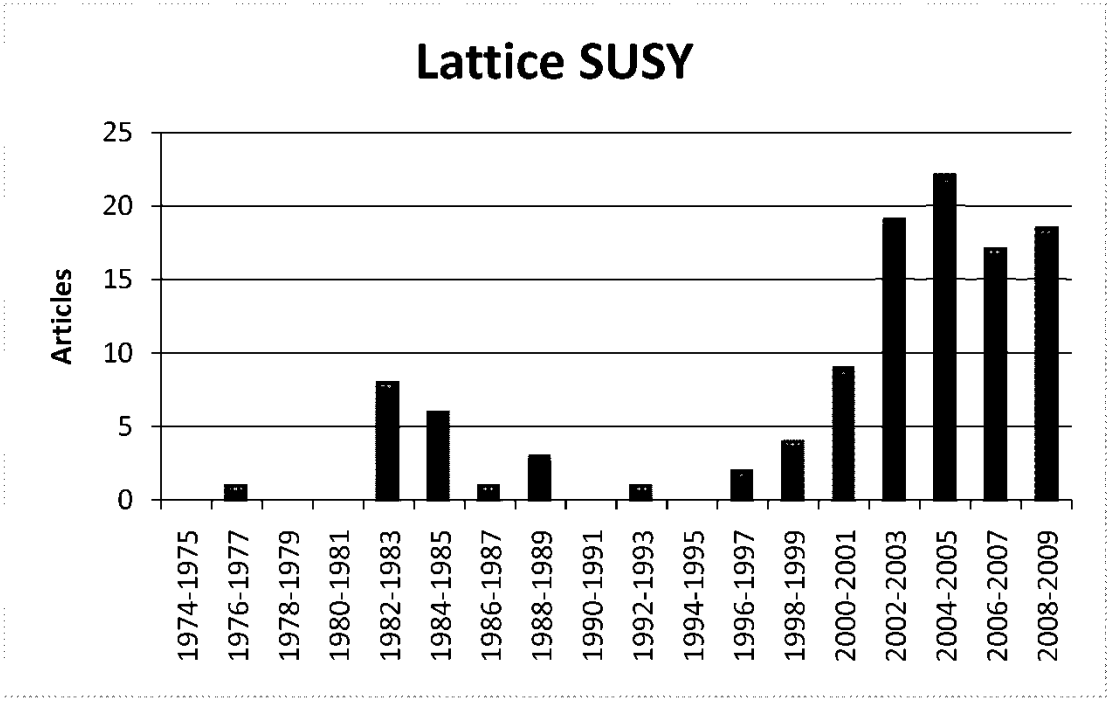


Program for $\mathcal{N}$=1

- Chiral limit requires $16^3 x 32 x L_s$ with $L_s > 48$.

  40 M hrs BG/L used.
- Better implementations DWF ?
- Spectrum calcs
- Non-perturbative renormalization
- Super QCD –Need fine tune scalar sector.
  - Accomplish by reweighting. Need runs over large parameter space – O(100) harder ! – future

Lattice SUSY: Emerging Field



Lattice BSM and experiment

- Current mode exploratory: develop tools/experience with non QCD theories
- Depending on LHC → hope focus on one or two theories of most interest in near future
- TC, SUSY, or something else ? Remain agile ..
- Long run:
  - Employ more significant hardware resources
  - Hope to predict quantities useful to model builders eg S parameter, technihadron spectrum for TC, soft breaking terms in MSSM, …

Summary

Exciting time for BSM studies on lattice!

year	percent BSM
2006-7	0.5
2007-8	4.2
2008-9	6.1
2009-10	7.1

Excludes 20 M hrs for N=1 SYM on BG/L and
Comparable amount for LSD N_f=6
DWF about to start on QCDOC

- Lattice studies can provide crucial non-perturbative info on TC, SUSY, …theories
- Current hardware/algs developed in QCD applicable.
- Exploratory and large scale simulations underway with LQCD resources